Abstract. We discuss spectral energy distributions of a sample of Herbig Ae/Be stars in the context of a passive irradiated disk model. The data have been presented earlier by **?**), and preliminary interpretations of these data were given in that paper. While the spectra of Herbig Ae stars all show similarities, there is significant variation between the spectra, in particular in the shape of the mid-IR rise and in the presence or absence of a silicate feature. We explore the hypothesis that all these different spectra can be interpreted as pure disk spectra without additional components. Using the model of Dullemond, Dominik and Natta (**?**) we deduce the disk parameters of a number of the sources, and find that for a large fraction of investigated sources, satisfactory fits can be obtained. The derived model parameters show that some group Ia sources can only be fit with radially increasing surface densities, indicating the presence of depleted inner disk regions. The steep-sloped SEDs of group IIa sources can be fit with very compact disks, probably representing disks with collapsed outer regions. The largest difficulties arise from sources that do not show significant silicate emission features. Our attempts to explain these objects with a pure geometric effect are only partially successful. It seems that these stars indeed require a strong depletion of small silicate grains.

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Understanding the spectra of isolated Herbig stars in the frame of a passive disk model

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1. Introduction

Herbig Ae/Be stars (herafter referred to as HAEBE stars) are thought to be young stellar objects of intermediate mass (**?????**). They are associated with large amounts of circumstellar matter, both gas and dust, and are found in or near star forming regions. In the seminal paper of **?**), HAEBEs were defined to be near a reflection nebulosity, because this ensured they are young and close to a star forming region. The close proximity to molecular cloud material in combination with limited angular resolution observations makes it hard to distinguish dust and gas emission from the loose surroundings from that of the circumstellar disk. However, objects have been found that are very similar to other HAEBEs but lack a reflection nebulosity (**?**, see e.g.)]1998ARAA..36..233W. These stars are called *isolated Herbig stars*. Hipparcos observations of the nearest HAEBE stars have confirmed their pre-main-sequence nature (**?**).

HAEBE stars have a strong infrared (IR) excess due to circumstellar dust, often carrying a considerable fraction of the total luminosity of the system. Mid-IR imaging has shown that some HAEBE stars have spatially extended emission at these wavelengths (**???**); these stars often (but not always) are of (early) B spectral type, and their emission can be understood in terms of heating of the surrounding molecular cloud by the strong UV radiation field of the young star, possibly in combination with a disk (**??**). However, the less luminous late B, and A type stars in the HAEBE class often show unresolved or compact emission in the mid-IR when observed with 4 meter class telescopes on a scale of 1–2 arcsec, corresponding to 100-200 AU at typical distances of 100 pc. Van den Ancker et al (private communication) have unsuccessfully tried to resolve several of the sources in the sample (HD 100546, HD 104237, HD 144432, HD 163296) with the ESO 3.6m telescope, finding only upper limit of typically 0.7". Other observations have succeeded resolving the emission of some stars (e.g. AB Aurigae (**?**), HD100546 (**?**), HD97048 (van Boeckel et al, in preparation)) and found compact sizes. The isolated Herbig stars usually show little or no reddening at optical wavelengths, which is remarkable given their large L_{IR}/L_* ratio. An obvious way to explain this observation is to assume a flattened, disk-like distribution of the gas and dust viewed at some intermediate inclination angle. This disk can be understood as the passively heated remnant of the accretion disk which was present during the initial phase of star formation, and is similar to disks seen around the lower mass T Tauri stars. Since such passive disks are believed to be the site of planet formation, HAEBE stars have gained considerable attention in recent years.

Obviously, the best way to determine the geometry of the circumstellar material around isolated HAEBE stars is by direct imaging. **?**) spatially resolved the millimeter continuum and line emission from the Herbig Ae star HD163296 and found an elongated structure. Submillimeter aperture synthesis images in CO lines show rotation profiles in a number of Herbig Ae stars, with rotational velocities consistent with a Keplerian disk (**????**). Based on this evidence one may conclude with some confidence that at least the outer parts of the circumstellar matter distribution around some (isolated) Herbig Ae stars are, just as in the case of T-Tauri stars, in fact rotating circumstellar disks.

Observations of the spatial distribution of the circumstellar matter closer to the star (inwards of about 100 AU) have not yet resulted in a clear picture. There seems to be conflicting evidence suggesting both a flattened and more spherical distribution of gas and dust. Near-IR and optical imaging using ground-based adaptive optics and HST in several cases shows the emission to be flattened (**????**). However, interferometric observations at 2 μm, probing the inner regions on scales below 10 AU, have shown little or no evidence for a disk-like geometry (**?**).

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In view of the scarcity of resolved observations at these spatial scales, it seems that the procedure of fitting a model to the observed SED is still a valuable tool to study the properties of circumstellar matter around young stars. Under the assumption that the circumstellar dust is in radiative equilibrium, the temperature of the dust can be calculated by solving the radiative transfer equation. By varying the density distribution and the dust composition, one can eventually find a good 'fit' to the data. One has to keep in mind however that this procedure can not uniquely determine the geometry and density distribution of the circumstellar matter. Often, a multitude of different parameter sets lead to equally good fits (**?**). This clearly means that the SED alone does not contain enough information about the geometry and dust distribution in these objects.

Nevertheless, model fitting can retrieve interesting information from the SED if one uses additional constraints to the density distribution. These constraints can be obtained from e.g. spectroscopic quantities (lines, features), or any kind of imaging data when available. In addition to this, one can add *physics* to the model. For instance, one could require the density distribution to be in hydrostatic equilibrium: a self-consistent disk model. A simple, but powerful model of this kind is the semi-analytic passive flaring disk model of **?**). This model naturally reproduces the shape of the spectrum of many Herbig Ae stars longwards of 6 micron. Moreover, as was first noted by **?**), if one correctly accounts for emission from the disk's inner rim, also the SED shortwards of 6 microns (the conspicuous 3 micron bump) can be explained. In a recent paper, Dullemond, Dominik & Natta (2001, henceforth DDN), presented such a self-consistent disk model including both the emission from the flaring part of the disk and from the inner rim. They found that emission from the hot inner rim (being hotter than the flaring disk and thus having a higher scale height) can account for the near-IR excess in the HAEBE star AB Aur; the DDN model for AB Aur is the first disk-only model that can account for the *entire* SED of AB Aur.

Encouraged by our success in fitting AB Aur, we decided to investigage the applicability of the DDN model to a wider sample of HAEBE stars. We use the sample described by **?**). This is a set of isolated Herbig Ae stars which was selected from a larger set of Herbig AeBe stars (**???**). To our knowledge, none of the stars (with the exception of AB Aur) shows any significant reflection nebulosity or significant extended emission on scales much larger than expected for a disk. This suggests that the SED is not contaminated by large scale dust clouds surrounding the object. The objects were further selected by their very low circumstellar extinction - typically 0.5 magnitudes or less. Exceptions are HD 142666 (0.9 mag) and HD 150193 (1.5 mag) (**?**, and private communication). In their paper, Meeus et al. presented combined ISO SWS/LWS spectra and literature photometry data of 14 Herbig Ae/Be stars, and found that these objects show both striking similarities in the spectrum, and important differences.

We will attempt to interpret this variety of spectra entirely in the context of the DDN model, without additional components. This way we can find out whether an isolated disk picture is sufficient to explain the SEDs of these stars. And if we can, we will see what we can learn from the deduced parameters. The paper is organized as follows. In section 2 we describe the sample. In section **??** the DDN model is introduced and we detail the fitting procedure. In section **??**, the obtained fits are shown and discussed. Finally, in section **??**, we reflect on the successes and failures of the model to reproduce the SEDs of isolated Herbig stars.

2. Sample and SEDs

We use the sample of isolated Herbig stars as given by Meeus et al. This is a group of 13 stars which have the properties of Herbig Ae stars, but which are not located very closely to star forming regions. The original sample contains 14 stars, but we removed 51 Oph because of its uncertain nature (**?**)). The remaining SEDs are shown in figs. **??**–**??**. The source of the IR excess in these stars is believed to originate from a disk. The SEDs of these sources is similar, but still shows considerable variation. All stars show the characteristic bump in the spectrum around 3 micron. At a wavelength of about 5 μm, the SEDs (νF_ν) show a local minimum, followed by the 10 μm region in which most stars show a prominent emission feature attributed to silicate. Longwards of 10 μm, the SEDs differ significantly. Meeus et al. found that the SEDs can be classified into two major groups, group I and group II, and they speculate that the difference between the groups can be attributed to geometry. Group I sources are objects in which the SED plotted as νF_ν stays high or even rises in the region between 20 μm and about 100 μm. Meeus et al. attribute this strong mid-IR component to a flaring disk. Group II sources on the other hand continue to decrease longwards of 20 μm (the "powerlaw component" in Meeus et al), their spectrum in this wavelength region is more consistent with that of a geometrically thin disk. Numerically, the distinction between groups I and II can be measured by the different fractions of stellar light emitted in the near IR (NIR) and far IR (FIR) region. Table **??** shows these quantities for all stars in the sample. The stellar flux $F_\star$ is measured by integrating the Kurucz model fit to the optical and UV spectrum. In order to compute the emission from the disk, we subtract the Kurucz model from the SED and integrate the excess flux from 2 μm to 7 μm to define $F_{\rm NIR}$ and from 7 μm to infinity to define $F_{\rm FIR}$. In the NIR, almost all stars emit between 10 and 30%, with significant variation from source to source. In the FIR, group I sources reprocess typically 20-30% of the stellar radiation, while the group II sources are closer to 15%. The total effect of NIR and FIR reprocessing can